Reprinted from COMPUTERS AND BIOMEDICAL RESEARCH, Vol. 1, No. 1, March 1967

Printed in U.S.A.

COMPUTERS AND BIOMEDICAL RESEARCH **1,** 50–64 (1967)

Dynamic Aortic Diameter Measurements *in vivo**

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A method has been described for measurement of the dynamic changes in internal aortic diameter following injection upstream of a radiopaque dye. The method makes use of information available in a video-angiocardiogram and requires special computer techniques to suppress total system noise. Tests to date have demonstrated the limits of accuracy and show it to be a useful technique that might be effectively applied in health and disease and to other structures as well.

INTRODUCTION

This paper describes a system for measuring the diameter of the thoracic aorta which uses the information obtainable through standard angiocardiography to calculate absolute as well as dynamic variations in artery diameter. From these measurements and simultaneous intravascular pressure measurements, calculation of aortic elasticity have been performed in dogs and humans without opening the chest.

Figure 1 gives a general outline of the system used. The three blocks labeled A, B, and C represent three physically, as well as functionally, separate areas in the laboratory. Block A is the catheterization laboratory where the experiments were performed. Block B shows the video-tape recording facility and diagramatically the special purpose window generator and diameter computer. The system makes use of a special purpose analog preprocessing system which dumps data via an analog-to-digital converter (ADC) into a general purpose digital computer. Block C shows the digital computer with its associated read and write interfaces. The general purpose digital computer is equipped with a hardware configuration and software implementation which permits it to be used in a real-time, time-shared mode from remote computer consoles.[1]

* This research was supported by a grant from the Utah Heart Association.

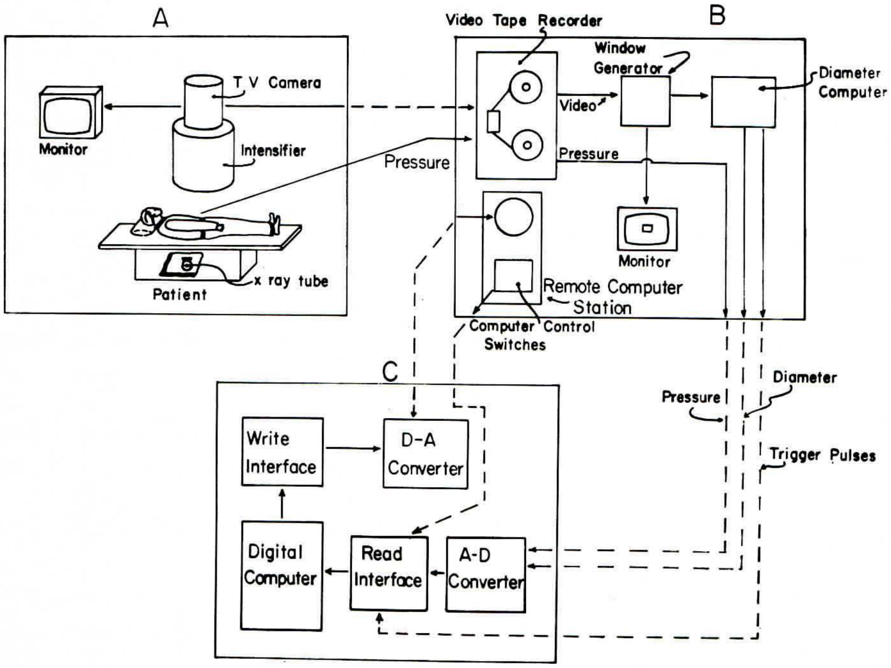

FIG. 1. Block diagram of system used to measure aortic diameter and elasticity.

I. DESCRIPTION OF CATHETERIZATION LABORATORY AND EXPERIMENTAL TECHNIQUES

All experiments were conducted in the catheterization laboratory shown in Block A of Fig. 1. This laboratory is equipped with a fluoroscopic television system which uses a 9-in. image-amplifier tube plus a mirror–lens system which sends this light signal to a low-level television camera containing an image orthicon camera tube. The television system, which is modified Westinghouse Televex, is a standard 525-lines/frame ($\frac{1}{30}$ sec) system. Each horizontal line requires only 63.5 μsec to traverse the width of the television screen. The image orthicon system is necessary for measuring dynamic diameter response because vidicons are inherently sticky and would be too slow to measure rapid responses of the pulsating aorta.

Also, a high-resolution X-ray system is used which contains a rotating anode with a 2-mm focal spot in order to eliminate X-ray optical effects of umbra and penumbra. The video signal from this television system is distributed to a video-tape recorder and also to a monitor in the catheterization laboratory which may be used during the experiment to watch placement of catheters and dye injections.

In experiments conducted using dogs, the animals were anesthetized with sodium pentobarbital (Nembutal) intravenous 30 mg/kg body weight. After the anesthesia had taken effect the dog was placed on a forced air respirator and catheters were inserted into both femoral arteries. One catheter was used to inject radiopaque dye and was usually a Bird's eye #6 French catheter. The second catheter was used for pressure measurement and was either a Statham Instruments SF1 catheter-tip manometer or a small (1-mm-o.d.) catheter connected to a Statham P23Db transducer exernally. The injection catheter was usually advanced until its tip lay in the arch of the aorta or in the descending aorta while the pressure catheter was advanced until its tip lay in the area where the diameter measurement was to be made, usually about 5 cm down the descending aorta. After catheters were in place the dog was then positioned such that his descending aorta was perpendicular to the horizontal lines of the fluoroscope system. This is done to simplify calibration but is not an absolute requirement if the geometry is taken into consideration.

With the dog so positioned, 30–35 cc of radiopaque dye (69% Renovist) were injected by a high-pressure injection syringe. This injection was usually complete within one to two seconds. The aorta is very well outlined with this amount of dye. Early problems were encountered when smaller doses of dye or slower injection rates were used in that the dye would streamline and the diameter-measuring system would measure the streamlining and give erroneous diameter information.

The fluoroscopic image of the chest was recorded on video tape equipped with a special FM edge track used to record pressure simultaneously (Fig. 1, block B). Although it is possible to process the data in real-time, the video tape offers the advantages of multiple playbacks and measurements of diameter from more than one site from a single injection.

In several experiments catheters were also introduced into the carotid artery or a femoral vein for infusion of drugs to either raise or lower mean pressure in order that the static and elastic characteristics of the artery could be checked over a much wider range than occurs normally with each heartbeat.

As a final step in each experiment, a steel rod with diameters of one, two, and three centimeters was placed in the fluoroscopic field at a level the aorta would normally occupy. Care was taken to place the image-amplifier pick-up surface at the same fixed distance above the table during the experiment as during the calibration in order to eliminate optical enlarging or reducing effects. Simultaneous pressure and diameter calibrations were then recorded on video tape for later processing.

II. DESCRIPTION OF VIDEO TAPE AND SPECIAL-EFFECTS WINDOW GENERATOR

The video tape used is an RCA Model TR2 with a special-effects window generator. This is a standard quadrature head machine similar to those used in commercial television studios. One voice track has been modified and is connected to a frequency modulator (FM) and discriminator such that it can be used to record static and dynamic pressures.

To select the proper section of aorta to be measured on a recorded run, a special electronic window generator is used to position a window over the area of interest. This window, whose size and position is easily varied, permits the selection of any rectangular area of the TV picture while suppressing the remainder. The fluoroscopic image shown in Fig. 2 was taken about one

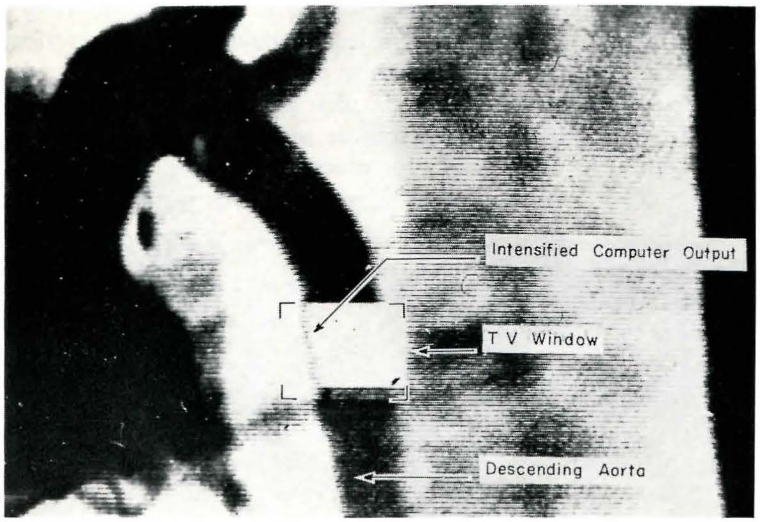

FIG. 2. Television fluoroscope of the chest of a dog after injection of radiopaque dye.

second after 35-cc radiopaque dye was injected into the left ventricle of a dog. As can be noted from the photo, the major arteries are well-outlined. The electronic window (indicated by the rectangular area in Figure 2) is positioned over the descending aorta and the signal from the window area is then processed by a special-purpose diameter computer.

The window generator used for this system was originally a special-effects generator supplied with the video tape. However, due to several limitations, a more-general-purpose window generator was constructed from commercially available logic cards (Computer Control Company S-PACS). It is a simple scheme which counts the number of vertical lines from the beginning of each field down to a selected vertical position. Upon reaching coincidence of the verticle position switch and the vertical position counter a horizontal position one-shot delay multivibrator (DM) is activated. Horizontal position is adjusted using a front-panel-mounted variable resistor to control the DM pulse width. The output of this DM then activates a horizontal-size DM which is adjusted for the desired horizontal window-size. Vertical dimension of the window is determined by counting the vertical lines after the window begins. This size is selected by a front-panel digital switch which selects the vertical window size and inhibits the action of the horizontal position DM on completion of a window.

The signal generated by the horizontal-size DM is used to gate the video signal from the output of the tape as well as to intensify the TV monitor. This intensifying signal provides a convenient method of positioning the window over the desired structure. The video window generator, as described in abbreviated form here, provides flexibility to the system since it can be used with any video-tape machine and can also be easily expanded to generate multiple windows as required for accurate videodensitometry.[2]

One horizontal line of video signal processed by the window generator is shown in Fig. 3. This oscillograph shows how the window generator gates

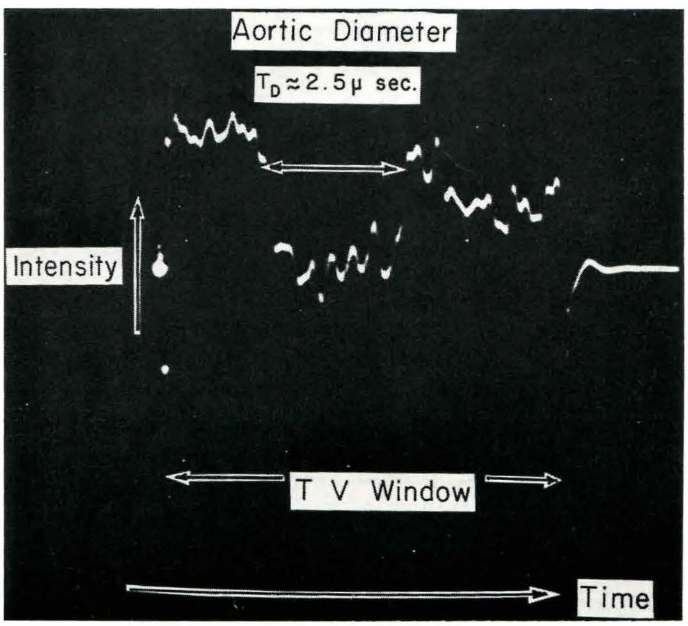

FIG. 3. Oscillogram of a single TV line as it crosses the aorta well-outlined with dye.

the video signal on and off, and demonstrates a typical signal produced following upstream injection of radiopaque dye into the descending aorta. As the sweep comes into the window, the light intensity is high until the beam reaches the left border of the aorta. There is then an abrupt decrease in light intensity, due to the radiopaque dye, which persists until the opposite side of the aorta is reached. The time for the beam to move between the two boundaries is directly proportional to the diameter of the aorta. The time interval of 2.5 μsec seen here is typical for dogs and represents a diameter of approximately 20 mm; thus, for this case we have a timewidth of 8 mm/μsec.

III. DIAMETER COMPUTER OPERATION

The special-purpose diameter computer constructed for use on this project is an assembly of both digital and analog elements operating in such a fashion as to take advantage of both.

Figure 4 outlines, in block diagram form, the computer layout and function.

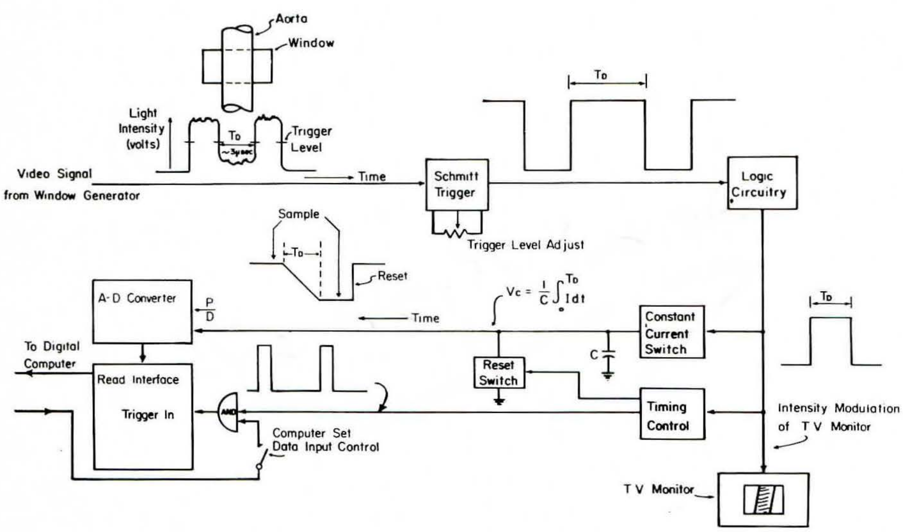

FIG. 4. Block diagram of the special-purpose diameter computer.

The input to the special-purpose diameter computer is the video signal from the window generator. This signal is fed after appropriate amplification into a Schmitt trigger which is manually set to trigger at the leading and trailing edges of the vessel. The pulse, whose width represents the vessel diameter, is then sorted out by use of logic circuits. The resulting pulse is used to turn on a constant current switch and generate a linear ramp. This same pulse provides timing pulses to trigger the ADC conversion and intensifying pulses for the TV monitor. The analog voltage representing diameter is digitized twice per TV line and the difference between these voltage levels is calibrated to represent vessel diameter in the computer.

An alternate approach would be to use the pulse representing the diameter to gate a high-speed counter and then send this count directly into the computer. This was indeed an early consideration, but it was decided that, for the time-accuracy capability of the video system (bandwidth 4.2 MHz with a rise time of about 10 nsec), the time-to-voltage conversion would be superior. The counter method would have required either sophisticated gating schemes or a gated 50-MHz counter to provide similar accuracy.[3] Since this method was expensive and difficult with commercially available hardware, the analog conversion method was used.

A more complete diagram of the diameter computer is shown in Fig. 5, with numbers indicating points at which the waveforms shown in Fig. 6 were recorded. The logic modules used are Computer Control Company S-PACS and the symbols used in Fig. 5 are for these modules.

The video signal which has been preprocessed by the window generator is distributed to a monitor and to the operational amplifier via a transistorized video-distribution amplifier. The operational amplifiers shown are Philbrick P-45 high-performance wideband amplifiers used to provide a voltage gain of up to 25 such that the Schmitt trigger (ST-10A) will function properly. The trigger level is manually adjustable from the front panel with a stable ten-turn potentiometer which permits adjustment of the trigger level between plus and minus two volts.

The system is self-synchronized, deriving all of the time information from the input video waveform and the window generator. Waveform 1 of Fig. 6 shows the video signal as it is applied to the ST-10A with the trigger level shown. Waveform 2 is the window pulse derived from the window generator and is used as a timing signal to assure that stray pulses do not disrupt the system timing. Waveform 3 shows the output of the ST-10A. The NAND gate following ST-10A is just a high-speed inverter. This NAND gate in turn drives a second five input NAND gate, a flip-flop (BC-12C) and (DM-11C). The action of the DM will be discussed first since the two other components depend on its action.

Assume that the system has been operating correctly for one video field. Then as the ST-10A output drops with the arrival of the video signal DM-11C will be activated by a positive pulse and generate a delay of about 3 msec, i.e., enough time for about 50 TV lines to be processed. Then by taking the negation output of this DM, a pulse 3 msec after the beginning of the window is generated which triggers the counter load one-shot DM-11B. This one-shot

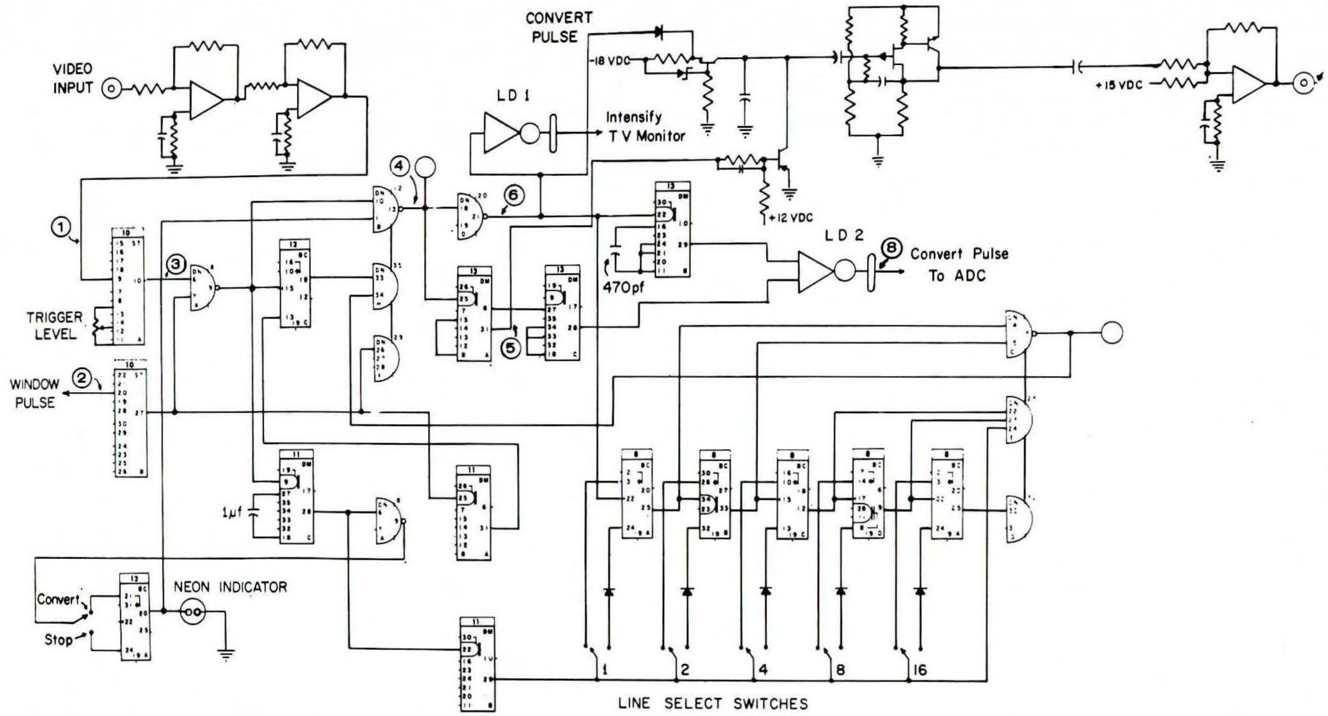

FIG. 5. Detailed diagram of the diameter computer.

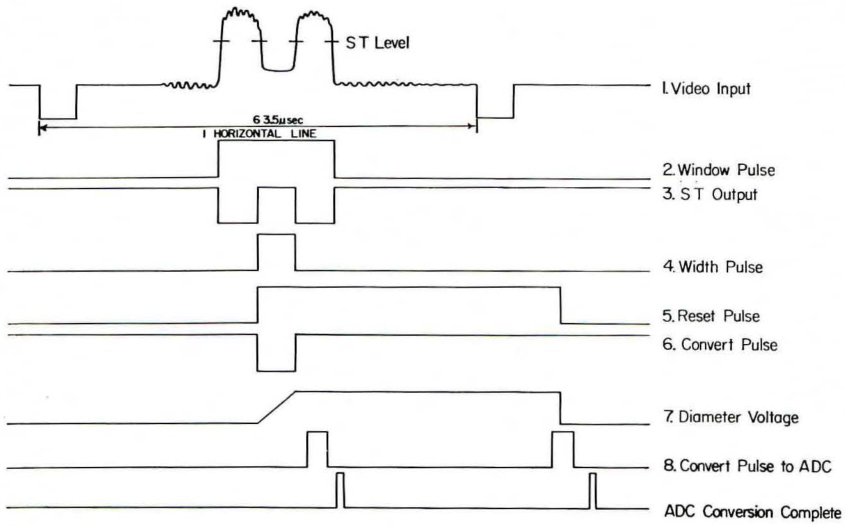

FIG. 6. Waveforms at key points in the diameter computer.

then "loads" the five flip-flops BC-8ABCD and BC-9A with the information contained in the number-of-lines select switches. These flip-flops are connected to count down the number of TV lines processed, and when the count reaches zero, the comparing NAND gate changes state and inhibits further video processing through the five-input NAND gate.

It can be seen that flip-flop BC-12C is a divide-by-two counter connected to the five-input NAND gate in such a way that it only allows the pulse from the ST-10A to get through the gate during the interval represented by the diameter. This flip-flop is reset at the beginning of each window by DM-11A to ensure proper timing for each field.

The function of the five-input NAND gate is to inhibit diameter pulses if any of the following conditions exist:

1. Data complete, countdown complete
2. Flip-flop BC-12C at the improper count
3. The selector switch in the STOP mode
4. No window pulse, i.e., vertical size pulse
5. Improper trigger pulse from ST-10A

The output of this NAND gate then represents, in pulsewidth, the time "width" of the artery (Fig. 6.4). To convert this timewidth to a voltage, which can in turn be digitized by an ADC, a gated integrator was built. This circuit is quite simple consisting of a fast-diode-gated constant-current source and a capacitor to "collect" the current.[4] The constant-current source is an NPN transistor with a Zener diode connected to its base. The current source is turned on when a negative voltage is applied to the gate and diode; otherwise it remains off. The PNP transistor in the reset gate is turned off for 40 μsec by DM-13A which is activated just as the diameter pulse appears (Fig. 6.5).

After integration of the constant current for the proper time the current gate turns off and the voltage is held on the capacitor until the 40-μsec period is over, during which time the ADC has been given a convert pulse and has sampled the analog signal. The integrator then resets and remains reset until the next line pulse triggers the current gate.

Generation of timing pulses for controlling the sampling is handled by two DM's, DM-13D and C, along with the coaxial cable linedriver LD-2. The waveforms and their relative timing are shown in Fig. 6.8. The conversion is initiated by the positive-going edge of the pulse and requires approximately 8 μsec to complete.

To minimize sag due to loading of the diameter holding-capacitor, the integrator output was coupled through a high-input-impedance field-effect transistor voltage-follower. From there the signal is AC coupled to another P-45 operational amplifier to provide bias and gain adjustments to make the system output compatible with the ADC.

Note that the analog signal is sampled twice per line such that any amplifier drift or level shift is eliminated so long as the system has gain stability. Also included in the circuitry is LD-1 which intensity-modulates the TV monitor enabling proper trigger level to be determined by viewing the TV monitor (see Fig. 2).

IV. OPERATION OF SYSTEM

The data was processed and displayed with the aid of the general-purpose Control Data 3200 computer available in our laboratory. Since processing of the video data requires sampling of the data at a very fast rate ($\cong$30 KHz) and requires external synchronizing, it was necessary during the usual two-second processing time to have full control and use of the computer. Since only two seconds of sampling time is needed and indicator lamps are available to indicate to other computer users when this mode of operation is in use, it is possible to process the data during the prime daytime shift. The computer is used to average multiple diameter-measurements per field ($1/60$ sec) since noise is sufficient to make diameter measurements from a single line too variable to be of value. This number of lines is under operator control and was usually selected to be ten or more.

Calibration data for diameter and pressure are entered into the computer by the investigator by replaying that segment of the video-tape recording containing the image of the calibration rod (one, two, and three centimeters) and the pressure calibration (0, 100, and 200 mmHg). The electronic window is positioned over the one-centimeter rod segment and the threshold is adjusted on the diameter computer until the intensity modulation of the TV image indicates the computer is triggering on the leading and trailing edge of the rod. Threshold adjustment may require replaying this segment of the tape several times. Once threshold is satisfactory the tape is played again and a push switch is pressed which generates an interrupt to initiate processing of the first diameter and pressure calibration signals. The other two calibration values of both variables are then processed in rapid succession. Since deviation from linearity for both diameter and pressure was less than three percent, a linear calibration is used. Once calibration constants are determined, they are used to process the remainder of the experimental data on that subject.

To measure aortic diameter and pressure from any given segment of the recording, a similar procedure is followed. When the segment of the tape record to be analyzed is located, it is replayed several times to permit proper positioning of the window over the aortic segment to be measured and to adjust threshold so that triggering is occurring at each edge of the aorta. On the next replay the digital computer is interrupted to begin sampling at the time when the aorta is well-defined by the injected dye.

The photo of the memory scope shown in Fig. 7 is a computer-output plot

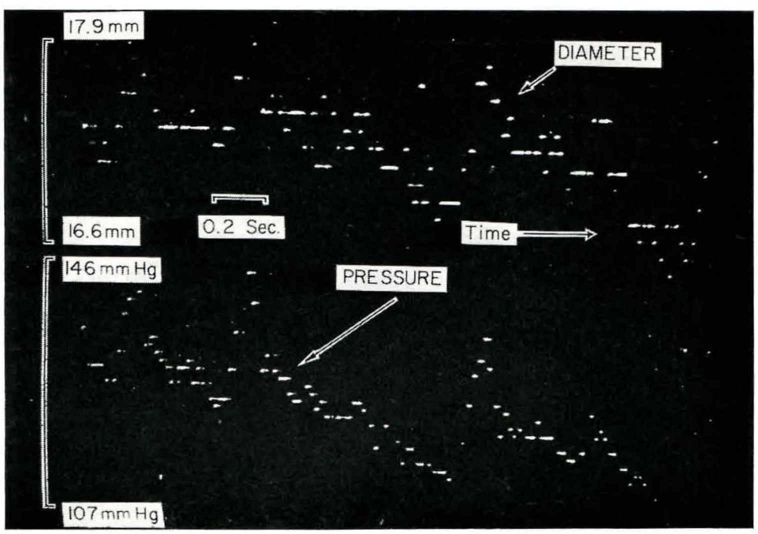

FIG. 7. Diameter and pressure vs. time as measured by the video technique.

of diameter and pressure as a function of time of data obtained from a fluoroscopic image of the dog's descending aorta. The upper trace shows diameter variations from 16.6 to 17.9 mm while the lower trace shows pressure variations from 107 to 146 mmHg. Note that the diameter variations follow the pressure variations even during the extrasystoles.

Since the video method has limitations and perhaps inaccuracies, three types of experiments were conducted to verify the video results. In the first series of experiments, a metal wedge (triangle) was connected to a linear position potentiometer. As the wedge was moved up and down in the X-ray field, an output voltage from this potentiometer was recorded on the FM track of the video tape. If the system had no storage or lag, the measured diameter should be directly proportional to the vertical position of the wedge in the field at all frequencies of wedge movement. Results of such tests indicate that the dynamic response is limited only by the 60-field/sec sampling rate of the TV system and not by lag in the image amplifier or TV camera.

The second series of experiments was designed to determine the minimum diameter difference measurable with the system. This was measured in the range and it was determined that difference in diameter of 0.4 mm could be measured with 95% confidence.

In the third series of checks, three dog experiments were performed in which the diameter was measured using a strain gage described by Mallos[5] and used by Patel.[6] The video was then checked by using the caliper technique as a standard. Care was taken to measure diameter at approximately the same point on the aorta with each method. Since there was interest not only in dynamic accuracy but also in static accuracy of the video method, Norepinephrine-induced hypertension, and hypotension caused by hemorrhage were used to expand the mean pressure and mean diameter range. Data from this type experiment showed that the strain gage caliper values were systematically larger than those of the video method by about 1.5 mm, which is of the order of two wall thicknesses in the aortas measured (mean diameter $\cong$ 18 mm). It should be pointed out here that the caliper measures external diameter and the video method measures internal diameter of the vessel. As a check of the dynamic accuracy and timing during the course of the cardiac cycle, experiments were performed with the strain gage diameter signal recorded on the FM track of the video tape. After proper calibration of both methods, a plot of each was displayed on a memory oscilloscope with the computer performing correlation on the data. Correlations between the two methods were usually 0.9 or greater, indicating that the video method was indeed accurate and properly time-correlated. Values of diameter variation were in the range of those reported in the literature as were calculated elastic properties over the extended mean pressure and diameter range.

V. CONCLUSION

The technique described suffers from some limitations; namely, the dye injection must be dense and well-mixed to assure that measurement is not affected by streamlining of dye flow, the system limit for resolution because of noise and bandwidth is about 0.44 m, and the television sweep and optical linearity are critical factors when making absolute measurements.

Despite these disadvantages the method offers some distinct advantages. It provides *in vivo* measurement in the intact animal of physical properties of the aorta; it requires a relatively easy operative procedure involving only introduction of catheters which is a currently used technique in humans; it measures internal not external diameter of vessels; it is a technique that makes dynamic measurements possible and, thus, allows calculation of elastic properties of the artery (transverse movement of the artery in the field does not affect measurement so long as the artery stays within the window); and finally, the major item of equipment is a video-tape recorder which has many other uses in a cardiovascular laboratory.

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